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Investigation of Engine Oil-cooling Problem during Idle Conditions on Pusher Type Turbo Prop Aircraft

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Abstract: Aircraft engines need a cooling system to keep the engine oil well within the temperature limits for continuous operation. The aircraft selected for this study is a typical pusher type Light Transport Aircraft (LTA) having twin turbo prop engines mounted at the aft end of the fuselage. Due to the pusher propeller configuration, effective oil cooling is a critical issue, especially during low-speed ground operations like engine idling and also in taxiing and initial climb. However, the possibility of utilizing the inflow induced by the propeller for oil cooling is the subject matter of investigation in this work. The oil cooler duct was designed to accommodate the required mass flow, estimated using the oil cooler performance graph. A series of experiments were carried out with and without oil cooler duct attached to the nacelle, in order to investigate the mass flow induced by the propeller and its adequacy to cool the engine oil. Experimental results show that the oil cooler positioned at roughly 25 % of the propeller radius from the nacelle center line leads to adequate cooling, without incorporating additional means. Furthermore, it is suggested to install a NACA scoop to minimize spillage drag by increasing pressure recovery.

Keywords: pusher aircraft, oil cooler duct, Engine Ground Run (EGR), mass flow rate, NACA scoop, spillage drag

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Introduction

LTA is a twin turboprop multi-role aircraft has low wings and pusher engines. This aircraft is powered by PT6A engines rated at 1,200 SHP [1] driving the propellers at 1,700 rpm. The oil-cooling system helps to drive sufficient air flow to cool the engine oil under specified operating conditions. The airflow requirements and engine oil flow characteristics are normally supplied by the engine manufacturer. Generally, in tractor type installations, the oil coolers are placed aft of the propellers and therefore the propeller slipstream provides sufficient cooling even during low forward speed conditions.

However, in pusher type installations, propeller slipstream is not available for driving the cooling airflow. Inadequate ram air during ground runs, taxiing and initial climb leads to excess engine oil temperature and as such positioning of the oil cooler duct is a critical issue. A high oil temperature may result in an increase in either the oil consumption rate or the amount of oil mist passing through the engine oil breather [2]. The standard cure for inadequate cooling is to operate the engine at much higher fuel flows resulting in reduced fuel efficiency [3]. A workaround is to provide a jet-pump (or ejector) inside the oil cooler duct, operated by compressor bleed air. Tapping of bleed air from the engine will impose additional load and this is more likely to cause a slight drop down in the inflow to the ECS.

An attempt has been made to find a solution to the oil cooling problem without utilizing compressor bleed and an ejector. The idea proposed is to utilize propeller inflow to induce flow through the oil cooler. In this experiment the oil cooler duct is positioned ahead of the propeller and air flow through the duct is induced by propeller suction. The scope of this study is to investigate the mass flow rate characteristics in the oil cooler duct and to compare it with the cooling requirements provided by the OEM. The proposed method aims at improving the engine efficiency as well as allowing the ECS to use dedicated bleed air, by avoiding ejector application.

The experiments were carried out in two steps. The first experiment was carried out without the oil cooler to identify the optimum location of the required air flow using a Pitot probe in the flow field surrounding the nacelle aft end. The approximate location of the oil cooler was fixed from the first experimental setup. Then, the second experiment was carried out with the oil cooler and duct in place to check the required air flow inside the duct. The test results were found promising.

Aspects of oil cooler duct design

The oil cooler duct is designed to capture the required mass flow with minimum pressure losses. For sizing calculations, a hot day climb at maximum climb rating is assumed as the flight condition. An altitude of 1,372 m, and a minimum desired flight speed of 67 m/s (EAS) in an atmosphere of ISA + 35 corresponding to an OAT of 41 °C are assumed. The required air flow to cool the oil depends upon the engine operating conditions and its heat rejection rate. For a power output of 1,000 SHP, the reference heat rejection (H_{ref}) is found to be 38 kW based on engine heat rejection curves [4]. In order to calculate the total heat rejection, the MOT at the maximum permissible value of 105 °C and the ambient temperature at 41 °C are considered. Based on the engine manual the THR is calculated as 38.15 kW.

For the oil cooler, the heat rejection is represented as a function of the airflow along with the air pressure drop. The airflow required can be read as a function of the Standard Heat Rejection (SHR) as defined below. The air flow (or) oil flow requirement for various engine power settings and the corresponding pressure drops is obtained from the oil cooler chart [4]. To simulate the SHR at the critical value the maximum oil flow rate is assumed to be 1.13 kg/s, as per the OEM requirements. The formula utilized for SHR calculation is as follows:

$$\mathrm{SHR} = \frac{\text{Heat Rejection X100}}{\mathrm{ITD}} \tag{1}$$

Where ITD = $T_{\text{in oil}} - T_{\text{in air}}$

For an ITD of 46 °C, SHR = 32.4 kW. Corresponding to this, the corrected air pressure drop is 165 mm of H_2O and the air flow is 1.5 kg/s. Using the inlet density ratio, the actual pressure drop calculated is 213 mm of H_2O for this configuration.

With a view to visualize the changes in both the THR and the SHR values with the ambient temperature, a ratio named HRR has been introduced, this HRR is the ratio between THR to SHR. A graph is plotted between the HRR and the ambient temperature considering different main oil temperatures as shown in Figure 1. It is seen clearly from the graph that the ambient temperature is inversely proportional to the HRR i. e. the amount of heat transferred from the oil to the airflow is greater when the ambient temperature of the air flow is lower. It is also seen that the HRR begins to slow down gradually once the ambient temperature surpasses 45 °C. In other words, the amount of energy transferred as a result of difference in temperature drops down once the ambient temperature starts rising above 45 °C.

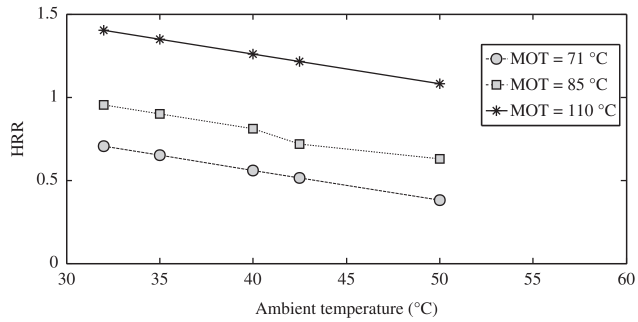

Figure 1: Heat rejection ratio (HRR) versus the ambient temperature (°C).

Achieving the OEM specified mass flow rate at the oil cooler duct is the central role that drives this design study. The duct inlet is said to be efficient if a large proportion of the available free stream total pressure is recovered at the oil cooler duct [4]. The air supply to the oil cooler duct is affected by a number of factors including the influence of the airframe. While designing the duct inlet, necessary care should be taken to optimize the inlet for required airflow. This pressure recovery is achieved by the appropriate NACA lips at the oil cooler duct inlet [5].

In the upstream and downstream of the oil cooler duct, the static pressure is equal to the ambient atmospheric pressure. Therefore, the exit dynamic pressure (q_e) is equal to the inlet dynamic pressure (q_i) minus the pressure losses. The exit dynamic pressure (q_e) is calculated by first assuming an exit area and a discharge coefficient. The discharge coefficient itself depends on the exit to inlet dynamic pressure ratio and the flow exit angle [6]. The flow exit angle is assumed to be 30° for which $\dot{m}$ = 0.827 kg/s and n = 0.14. The discharge coefficient is estimated by the following formula [7]:

$$C_D = \dot{m}\left(\frac{q_e}{q_i}\right)^n \tag{2}$$

The exit area is adjusted in such a way that the assumed matches with the calculated values. The variation of the discharge coefficient with respect to the exit pressure ratio is shown in Figure 2. The discharge coefficient C_D is a function of the exit pressure ratio. It may be noted that the calculated ratios of the exit dynamic pressure to the inlet dynamic pressure are in the order of 10 and 15 percentage of the parallel and NACA diverging wall inlet respectively. As such the exit area needs to be significantly higher than the inlet area. The ratio of exit area to inlet area obtained for the NACA inlet is 1.9 [5]. The ratio of exit area to inlet area calculated for the oil cooler duct is 1.8.

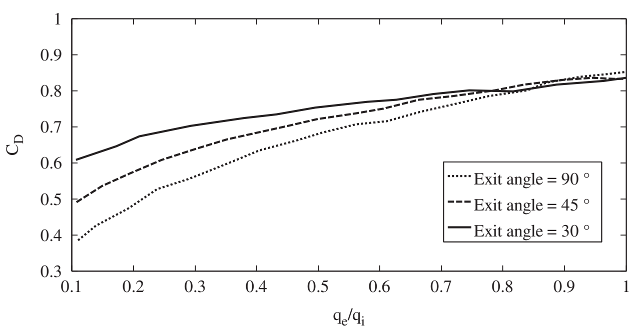

Figure 2: Discharge coefficient vs exit pressure ratio.

Once the exit area is sized to allow the required mass flow at a certain speed, the inlet area sizing is straightforward, since the required mass flow and the free stream to inlet velocity ratios are known.

$$A_i = \frac{\dot{m}}{\rho V_i} \tag{3}$$

Where $V_i = V_0$, for parallel wall inlet and $V_0/2.0$ for the NACA inlet.

From the above equation, calculations for the parallel wall inlet and the NACA inlet for an OAT of 32 °C and OAT of 42 °C were done by assuming exit area 0.08 m^2 for all cases [8]. It is seen that at an OAT of 32 °C the parallel wall inlet gives the required mass flow at a climb speed of 54 m/s while the NACA inlet gives the same performance at 44 m/s. At an OAT of 42 °C the required climb speeds are higher: 85 m/s (EAS) for the parallel wall and 71 m/s (EAS) for the NACA inlet. In any case the NACA inlet seems preferable. The general shape of NACA wall and parallel wall inlets are shown in Figure 3 [8]. The results of these calculations are discussed later. The existing inlet and exit areas of the oil cooler duct are 0.05 m^2 and 0.07 m^2. The effective exit area of the oil cooler within the duct is 0.06 m^2. The resulting shape of the oil cooler upstream and downstream ducts along with oil cooler generated using CATIA design software is shown in Figure 4.

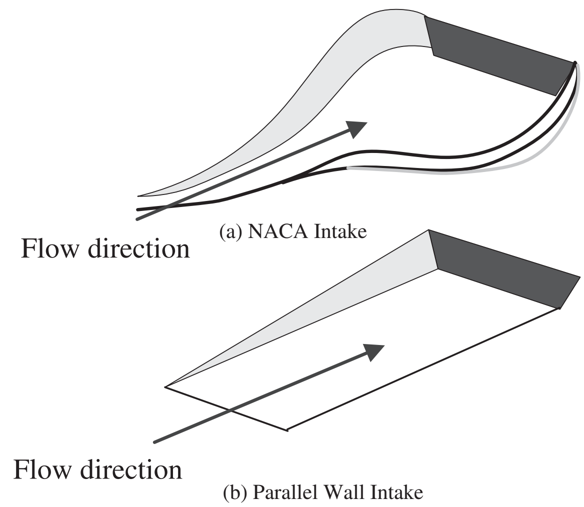

Figure 3: Shape of NACA wall and parallel wall inlet.

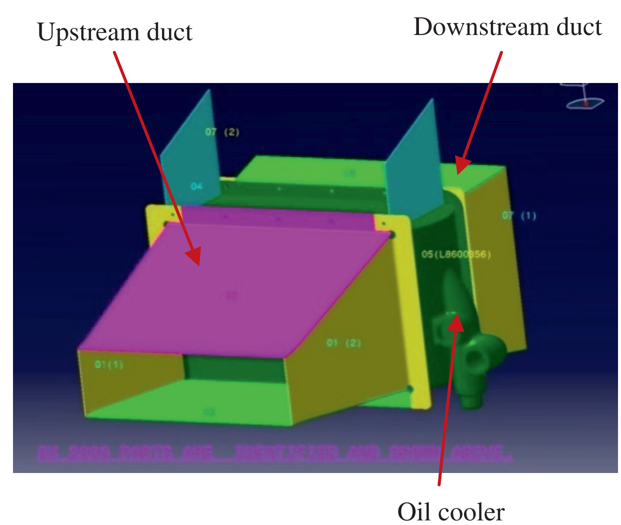

Figure 4: CATIA design of oil cooler duct geometry.

Experimental setup

Efficiency of the oil cooling system greatly depends upon the location and the required mass flow rate of the system. The position of oil cooler system is critical in pusher type aircraft. This is due to the inadequate air supply directed through the duct to cool the oil. Therefore, it becomes important to install the oil cooler duct at its optimum location providing adequate mass flow rate. Hence, ground test experiments were set up to find the optimum location where the mass flow rate matches with the design requirements. The oil cooler duct was installed at the bottom of the nacelle so that adequate air supply to the oil cooler duct could be achieved by the entrainment induced by the propeller. But, in order to find a suitable location for the installation of oil cooler duct the experiments were done in two steps. The first experiment was conducted using Pitot probe to measure the pressure at different pre-identified locations from the nacelle center line. The Pitot tube was placed at different heights from the nacelle centre line to find out the optimum position. The first set of experiments was made at position 1(P_1) and position 2 (P_2) as shown in Figure 5. Measured Pitot probe pressure values were then converted into velocity using Bernoulli's equation and compared with the OEM requirement deduced from its design specifications. Based on the measurements of the first experimental set up, the optimum position for installation of oil cooler duct was identified to proceed to the next level of experiments using oil cooler duct. Further the experiments were conducted by locating the oil cooler duct in the final position. The oil cooler duct assembly is attached to the final position identified on the aircraft rear nacelle temporarily using rivets for testing as shown in Figure 6.

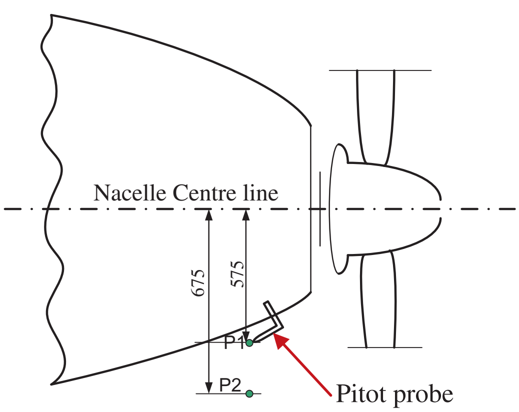

Figure 5: Pitot probe positions (P1 and P2) from nacelle centre line.

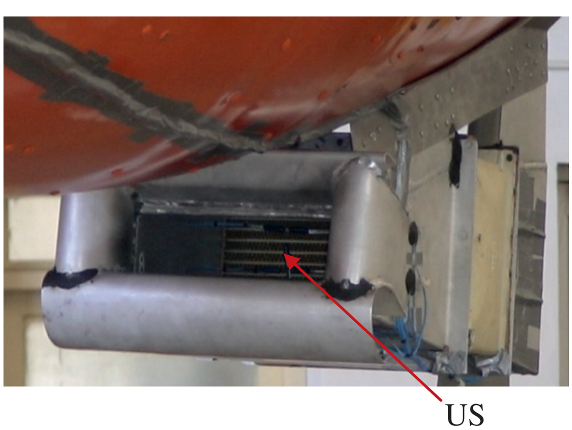

Figure 6: Oil cooler duct mounted in the final position of engine nacelle.

The sensors in the upstream and the downstream were located in such a way that they measure the flow velocity at the same point by forming a plane and five sensors were placed at the upstream duct and another five at the downstream duct [9].The sensor arrangements of upstream and downstream oil cooler ducts are shown in Figures 6 and 7 respectively. This second experiment utilized DAS to measure the velocity using sensors at upstream and downstream of the oil cooler duct which is shown in Figure 8. When positioning sensors in the flow, care was taken that flow is not blocked off or redirected. To overcome this XS clip-on sensors were used. Being smaller than the low-profile clip-on series sensors, XS allows for reduced obstruction. A smaller sensor can minimize obstructions and henceforth can give readings that are more precise. The XS clip-on sensors are shaped like a blade, to be positioned parallel to the current flow. The sensors are excellent for board level analysis in electronics cooling, and can even be inserted in the gaps between the fins of wider heat sinks. Hence, the air flow and the velocity data at different positions at upstream and downstream of the oil cooler duct were obtained by the DAS using XS sensors at a greater precision. Table 1 gives the specification of DAS and XS sensors.

Figure 7: Sensor arrangements in the downstream duct.

Experimental observed using DAS was compared against the design data for validation. After obtaining the validation the oil cooler system was installed in the right position featuring design air flow through the duct to provide proper cooling. The oil cooler system mounted on the pusher type turbo prop engine during the experiments is shown in Figure 9.

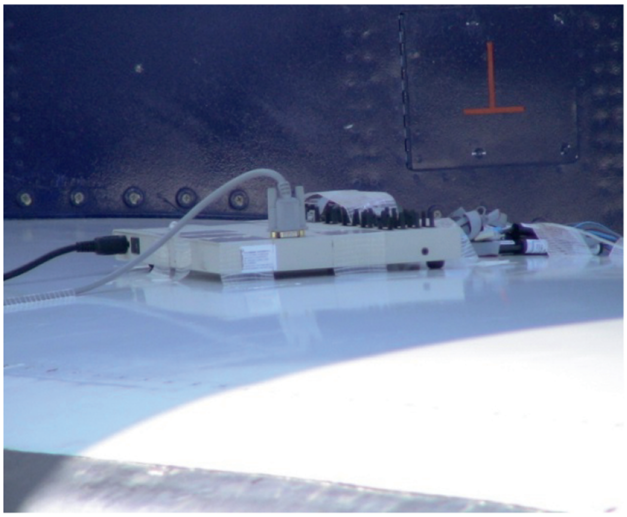

Figure 8: DAS used to measure the time series velocity.

Table 1: DAS and XS sensors specification.

Type of sensor	Air velocity and temperature sensors
Model	XS-Type
Air flow range	5.0–20.0 m/s
Temperature range	0–100 °C
Data acquisition	Accutrac-4.0
Time constant	200 ms
Warm-up time	< 10 s
Compensation range	0–70 °C
Mechanical dimensions	Sensor head width: 4 mm
	Length: 21 mm
	Thickness: 1 mm

Figure 9: Pusher type turbo prop aircraft mounted with oil cooler duct assembly during EGR.

Results and discussions

The oil cooler duct geometry was designed for effective cooling of oil based on the OEM's design specification. After designing the duct geometry, to effectively position the oil cooler system, pressure measurements were made at different locations from the nacelle center line using Pitot probe. Based on the experimental observations oil cooler system has been installed on the aircraft. Further, the mass flow rate requirements of the oil cooler system were determined by measuring the velocity at upstream and downstream of the oil cooler ducts. The results of the design process and experiments are discussed in the following section.

Oil cooler duct geometry

The variation of minimum climb speed with exit area of NACA and parallel wall inlets is shown in Figure 10 for two different OAT. From the figure, it is seen that at an OAT of 32 °C the parallel wall inlet will give the required air flow for cooling at a climb speed of 58 m/s (EAS) while the NACA inlet can give the same performance at 46 m/s (EAS). At an OAT of 42 °C the required climb speeds are higher: 90 m/s (EAS) for the parallel wall and 74 m/s (EAS) for the NACA inlet. It is seen that for the NACA inlet beyond an exit area of 0.08 m^2 the improvement in climb speed is not significant. The inlet area of the parallel wall inlet is 0.02 m^2 and the NACA inlet is 0.04 m^2. Therefore, for the NACA inlet duct the inlet to exit area ratio is 2.0. The existing inlet and exit areas of the oil cooler duct are 0.05 m^2 and 0.07 m^2. The effective area of the oil cooler within the duct is 0.06 m^2. In any case the NACA inlet seems to be preferable by comparing the results from Figure 10.

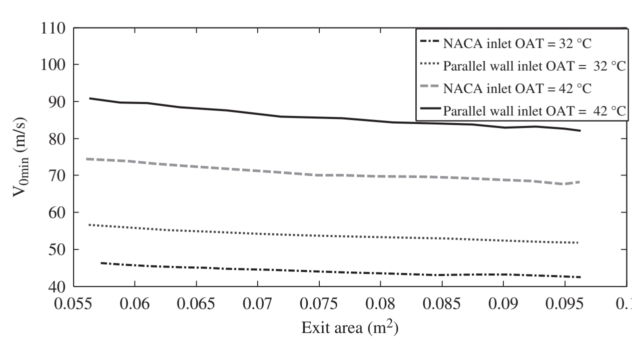

Figure 10: Minimum climbing speed vs exit area for OAT 32 °C and OAT 42 °C.

Pressure measurement using Pitot probe

Using the first experimental setup the pressure at two different locations was measured on the rear nacelle using Pitot probe. The tests were carried out by placing the Pitot probe at position-1 and 2 from the nacelle center line in the upstream of the propeller. Table 2 shows the test results for flight idle conditions, from the results it is evident that the velocity at position-2 is higher compared to position-1. To meet the mass flow requirement by considering duct losses on the aircraft, 675 mm nacelle center line location was selected for further testing with oil cooler duct experimental setup.

Table 2: Probe position and experimental values.

Description	Position-1	Position-2
Condition	Flight Idle	
Probe position (From Nacelle centre line in mm)	575	675
Pitot Probe reading (in mm of H_2O)	4.57	5.6
Velocity required in oil-cooler	8.6	
Calculated velocity (in m/s)	8.73	9.66

Velocity measurements at upstream and downstream of oil cooler duct

In the second experimental setup air flow was measured directly using airflow sensors in the upstream and downstream oil cooler ducts. The airflow was measured using ten sensors, five at upstream duct and five at downstream duct, during EGR. Totally 124 data points were measured in 1,809 s with a sample interval of 15 s for each sensor. Figure 11 shows the experimental results measured by sensors during EGR. It shows the average values of upstream and downstream sensor data.

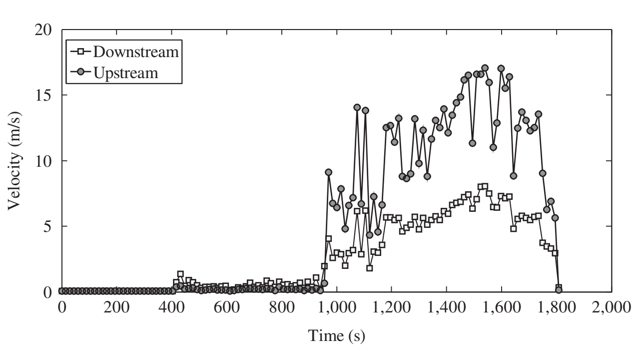

Figure 11: Velocity data at the upstream and downstream of the oil cooler.

From Figure 11 it can be observed that, the velocity measured at downstream is less compared to the upstream measurement due to oil cooler placement. After engine start during EGR, the flight idle phase was observed between 971 s and 1,240 s approximately. After averaging the probe measurement values, the average velocity at upstream of the oil cooler during flight idle condition was observed as 9.3 m/s. This measured velocity is less than the comparable velocity for first experimental setup results due to duct losses. The measured velocity using a second experimental setup with oil cooler duct satisfies the OEM requirement which is mentioned as 8.6 m/s during critical condition.

Oil cooler duct installation

A good inlet design thus maximizes pressure recovery, while at the same time minimizing drag, pressure distortions, weight, cost and a number of other constraints [4]. The two basic types of inlets namely the rectangular plan form and the curved divergent plan form is shown in Figure 12. The rectangular plan form is easy to manufacture whereas the curved-divergent plan form with highly swept plan form produces strong vortices along the ramp side which reduces the pressure loss [5]. Hence, curved divergent plan form is preferred over a rectangular plan form to minimize the pressure loss. The recommended NACA plan form shape of the oil cooler duct, which can be used for installation on nacelle, is shown in Figure 13. The NACA inlet is placed at the bottom of the nacelle such that the inlet ramp lies between the L-frame and the M-frame. Subsequently, the oil cooler is placed in a suitable location behind the inlet, such that the distance between the inlet throat and the oil cooler face is roughly 0.03 m. An aggressive diffusion is permissible due to the significant resistance offered by the oil cooler. The duct from the back of the oil cooler face is gradually adjusted to the exit area. The exit area of our downstream duct is 0.07 m^2. The aspect ratio of the exit is kept equal to that of the oil cooler face, which is roughly 1.4.

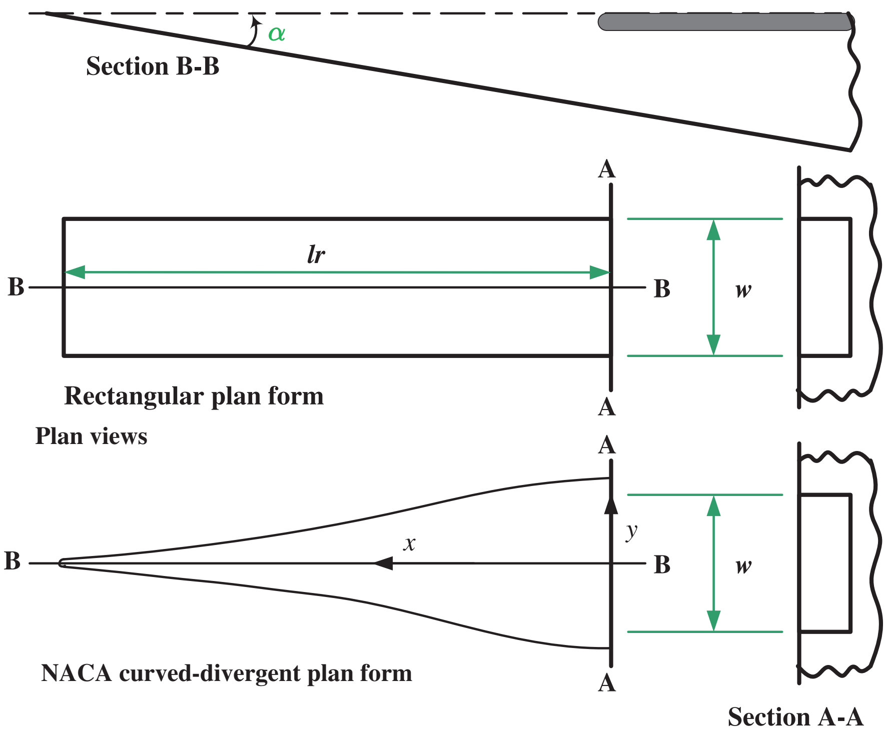

Figure 12: Plan form geometry of the rectangular and NACA inlets.

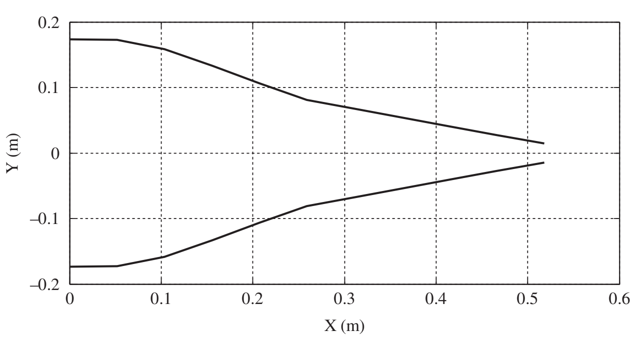

Figure 13: Recommended NACA inlet plan form.

Conclusions

An analysis is made on the design of oil cooler duct geometry and its optimized location. Mass flow rate, NACA scoop design, velocities upstream and downstream, etc. are discussed in detail. The following conclusions are made out of the investigation.

1. Design and sizing of the oil cooler duct has been made as per the critical design requirement without affecting the OEM specified mass flow rate.
2. Optimum location of oil cooler duct from the nacelle centre line has been identified in such a way that the velocity measured is more than the velocity required as per the cooling requirements.
3. Adequate mass flow rate has been achieved at the oil cooler duct location which was identified based on the velocity measurements of the experiments and appropriate duct installation on aircraft is also recommended.

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Nomenclature

α	Oil cooler inlet ramp angle in degrees
ρ	Density in kg/m^3
$\dot{m}$	Mass flow rate in kg/hr

A	Area in m^2
L	Length in m
q	Dynamic pressure in N/m^2
V	Velocity in m/s
w	Highlight width in m
C_D	Discharge Coefficient
CATIA	Computer Aided Three Dimensional Interactive Application
DAS	Data Acquisition System
DS	Downstream
EAS	Equivalent Air Speed in m/s
ECS	Environmental Control System
EGR	Engine Ground Run
ESDU	Engineering Sciences Data Unit
HRR	Heat Rejection Ratio
ISA	International Standard Atmosphere
ITD	Inlet Temperature Difference
LTA	Light Transport Aircraft
MOT	Main Oil Temperature °C
NACA	National Advisory Committee for Aeronautics
OAT	Outside Air Temperature in °C
OEM	Original Equipment Manufacturer
RPM	Revolutions per Minute
SHP	Shaft Horse Power in HP
SHR	Standard Heat Rejection in kW
THR	Total Heat Rejection in kW
US	Upstream
XS	Extra Small

Subscripts

e	Exit
i	Inlet
o	Outlet
r	Ramp

Superscripts

n	Flow exponent

References

1. Lathasree P, Pashilkar AA. Digital simulation model for a turboprop engine. Symposium on Applied Aerodynamics and Design of Aerospace Vehicle (SAROD 2011), Nov 2011.
2. Know your PT6A Turboprop. Engine Introduction Manual, Pratt & Whitney Canada.
3. Milley SJ, Ovens JK, Lawrence DL. An experimental investigation of the aerodynamics and cooling of a horizontally-opposed air-cooled aircraft engine installation. NASA Contractor Report 3405.
4. ESDU86002 – Drag and pressure recovery characteristics of auxiliary air inlets at subsonic speeds, issued Apr 1986.
5. ESDU66028 – Relationships between some common intake parameters, issued July 1966.
6. Sóbester A. Tradeoffs in jet inlet design: a historical perspective. J Aircraft May–June 2007;44. DOI: 10.2514/1.26830.
7. Dewey PE, Vick AR. An investigation of the discharge and drag characteristics of auxiliary-air outlets discharging into a transonic stream. NACA Technical Note 3466.
8. Mossman EA. A comparison of two submerged inlets at subsonic and transonic speeds. NACA RM A9F16.
9. Doebelin E. Measurement systems application and design. McGraw Hill, Columbus, U.S.A., 2003.